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Discrete Optimization

Incorporating ergonomic risks into assembly line balancing

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ABSTRACT

In manufacturing, control of ergonomic risks at manual workplaces is a necessity commanded by legislation, care for health of workers and economic considerations. Methods for estimating ergonomic risks of workplaces are integrated into production routines at most firms that use the assembly-type of production. Assembly line re-balancing, i.e., re-assignment of tasks to workers, is an effective and, in case that no additional workstations are required, inexpensive method to reduce ergonomic risks. In our article, we show that even though most ergonomic risk estimation methods involve nonlinear functions, they can be integrated into assembly line balancing techniques at low additional computational cost. Our computational experiments indicate that re-balancing often leads to a substantial mitigation of ergonomic risks.

1. Introduction

The problem of unfavorable working conditions, or poor workplace ergonomics, is an acute topic today. Ergonomic risks at the workplace cause a lot of damage on health and quality of life of workers, deteriorate economic results of employers and of the economy as a whole. In 2008, along 315,000 cases of work-related musculoskeletal disorders (MSDs, often referred to as ergonomic injuries), requiring a median of 10 days away from work, were reported in the US (Bureau of Labor Statistics, 2009). Annual compensation cost for MSDs paid by employers in the US amount to 15 to 20 billion US dollars. Moreover, occupational diseases of workers indirectly cause further cost on firms: via loss of production capacity due to absenteeism of workers, lower worker productivity and higher defect rates in work. This can be illustrated by the example of Peugeot, whose ergonomics program reduced the cycle time for the final vehicle assembly line together with a simultaneous decrease by 30% in new cases of musculoskeletal disorders (Moreau, 2003).

Workplace ergonomics is becoming even more important following recent developments in legislation (EU Machinery directive, 2006/42/EC, 89/391/EEC, Occupational Safety and Health act of 1970 among others) and an on-going ageing of the workforce in most of the developed countries.

Already today in assembly line production, especially in final assembly, where the share of manual labor is high, a special attention is paid to ergonomics. Most renowned companies incorporate methods for ergonomic risk estimation of working places in their production routine (Toyota Verification of Assembly Line at Toyota, GM-UAW at General Motors, AP-Ergo at Volkswagen to name a few). If ergonomic risks are detected, re-balancing of the assembly line is recommended as an effective method in the short-run (Hilla, 2006).

Ergonomic aspects have been barely considered in assembly line balancing literature, though they are becoming increasingly important in practice. Few articles on this topic are those of Miralles et al. (2008) and Costa and Miralles (2009), who introduce and analyze a problem of assigning workloads to stations and to workers with different (dis-) abilities. Another article, written by Carnahan et al. (2001), examines an assignment of a certain class of tasks – gripping tasks – and their influence on fatigue and recovery dynamics of workers. However, to our best knowledge, no attempt has been made yet to incorporate ergonomic risk estimation methods used in practice into assembly line balancing models, though they are considered important by manufacturers.

To close this gap, we address this important question in the present study. We provide an overview of some methods for ergonomic risks estimation, which are recommended and utilized in practice. Most of those methods are based on nonlinear functions such that incorporating them into state-of-the-art line balancing models and (exact) solution procedures is not straightforward.

We propose different ways to model ergonomic aspects and a two-stage heuristic approach, based on the well-known exact balancing procedure SALOME and the heuristic meta-strategy simulated annealing. By means of this heuristic approach, we can achieve a significant reduction in ergonomic risks of workplaces at low computational cost even without increasing manufacturing capacity, i.e., number of workstations (and workers). The proposed

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two-stage heuristic approach, furthermore, allows for a controllable increase in manufacturing capacity considering the trade-off between increased costs from adding stations on the one hand and reduced ergonomic risks on the other hand.

We precede with an overview of ergonomics tools in Section 2. A line balancing problem incorporating ergonomic risk factors, ErgoSALBP, is described and modeled in Section 3. In Section 4, we propose a two-stage heuristic, which is tested in comprehensive computational experiments in Section 5. A discussion in Section 6 concludes the paper.

2. Methods for estimating ergonomic risks

In the mandatory Appendix D.1 to §1910.900 of "Final Ergonomics Program Standard", the Occupational Safety and Health Administration (2000; OSHA for short) provides a list of methods recommended for the estimation of ergonomic risks of workplaces. In this section, we provide a brief description of selected methods recommended by OSHA for application in assembly line production – the revised NIOSH (the National Institute for Occupational Safety and Health) equation and the job strain index; the method OCRA (OCcupational Repetitive Action) recommended by European Norms on repetitive actions (EN 1005-5, 2007) and the EAWS (European Assembly Worksheet) method, which was created for and adapted by several European firms that employ an assembly production system.

Throughout the paper, we will use an example of an assembly line, the precedence graph for which is given in Fig. 1. The graph consists of $n = 11$ tasks $i = 1,\ldots,n$ with task times t_i to be executed on each workpiece at a workstation during the cycle time of $c = 63$ seconds. Every task involves several actions of upper limbs, while some of them demand application of forces (see Table 1).

2.1. Risk estimation for manual handling: revised NIOSH equation

The NIOSH equation was developed in 1981 by the National Institute for Occupational Safety and Health for risk estimation of working conditions, where manual handling activities are the main source of risk and lifting comprises more than 90% of manual handling activities (Waters et al., 1994).

The NIOSH equation communicates a lifting index *LI* that shows the relation of the current load weight to the recommended load weight limit:

$$LI = \frac{\text{Load weight}}{\text{Recommended weight limit}} \quad (1)$$

The higher the lifting index, the higher percentage of the workforce is likely to be under risk for developing low back pain. The recommended weight limit is calculated depending on lifting conditions *TS*, e. g. vertical travel distance of hands or degree of asymmetry in posture, and the frequency of lifting *FM*:

$$\text{Recommended weight limit} = TS \cdot FM \quad (2)$$

The frequency multiplier *FM* is calculated based on the average number of lifts per minute. It takes into account the duration of

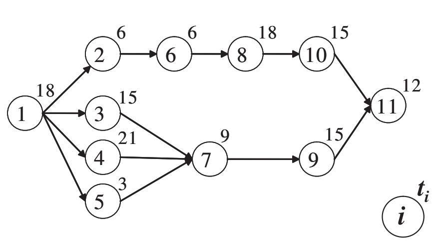

Fig. 1. Example of a precedence graph.

Table 1
Example of an assembly line. Task description for the right hand. Cycle time is 63 seconds.

TaskNo.	Task time (seconds)	Actions	Posture	Average force, % of max force capacity (MFC)
1	18	8	Hand grip (wide)	20%
2	6	2	Elbow flexion > 60°	5%
3	15	5	Elbow flexion > 60°	Insignificant
4	21	6	Elbow flexion > 60°	10%
5	3	5	Hand grip (wide)	33%
6	6	2	Neutral posture	1 lifting of 17 kg (avg. force of 70%)
7	9	2	Neutral posture	1 lifting of 15 kg (avg. force of 40%)
8	18	3	Dorsal flexion	20%
9	15	4	Neutral posture	33%
10	15	3	Dorsal flexion	25%
11	12	11	Dorsal flexion	10%

Table 2
Frequency multiplier FM for 2–8 hours of continuous lifting and lift height $\geqslant$30 cm.

Frequency: lifts/min	$\leqslant$0.2	0.5	1	2	3	4	...
FM	0.85	0.81	0.75	0.65	0.55	0.45	...

the lifting activity, as well as the vertical height of the lift from the floor. In Table 2, we present frequency multipliers for 2–8 hours of continuous lifting and vertical lift height of 30 cm or more. *TS* considers task specific parameters and indicates the *maximal* recommended weight of the load that can be lifted by healthy workers under certain lifting conditions. For example, under the ergonomically most favorable lifting conditions (e. g. when the weight is held close to the body), *TS* is equal to 23 kg.

In our example, let us assume that tasks 6 and 7 are performed on the same station. The worker lifts – under ergonomically favorable lifting conditions – a 17 kg and a 15 kg load in each cycle of 63 seconds (see Table 1). The task specific parameter *TS* for both cases of lifting has the ideal value of 23 kg and the frequency multiplier *FM* for both cases is 0.7557 (60/63 = 0.9524 lifts per minute, the value of *FM* is retrieved from Table 2 by interpolation). So, the recommended weight limit is 17.38 kg and the resulting lifting indices are 0.98 for task 6 and 0.86 for task 7.

In case of several lifting tasks, we compute the *composite* lifting index *CLI* as follows:

$$CLI = LI_1^1 + \left(LI_{1,2}^2 - LI_1^2\right) + \left(LI_{1,2,3}^3 - LI_{1,2}^3\right) + \cdots \quad (3)$$

$LI^j_{1,\ldots,i}$ is calculated for the lifting task *j* based on the cumulated frequency of the tasks $1,2,\ldots,i$. Tasks are numbered in non-increasing order of their individual lifting indices LI^j_j. Generally, composite $CLI \leqslant 1$ is considered to be acceptable.

For a station load consisting of tasks 6 and 7, we get $LI_1^1 = 0.98$ and $LI_1^2 = 0.86$ as explained above as well as $LI_{1,2}^2 = 0.99$, which corresponds to two lifts of 15 kg in 63 seconds, so that the composite index *CLI* amounts to 1.11. Usually, this work load is considered unacceptable.

Similar Methods. Several other methods are constructed according to the logics of the revised NIOSH lifting equation, e.g., the Siemens method (Bokranz and Landau, 2006). Additionally, the Siemens lifting index takes into account *FI*, a factor that is dependent on demographic characteristics and fitness of the worker:

$$LI = \frac{\text{Load weight}}{\text{Recommended weight limit}} = \frac{\text{Load weight}}{FI \cdot FM \cdot TS} \quad (4)$$